Soil Water Depletion and Root Distribution of Three Dryland Crops

T. S. Moroke,* R. C. Schwartz, K. W. Brown, and A. S. R. Juo

ABSTRACT

Characterization of plant uptake of soil water at different points in time and space are important in evaluating seasonal water use as well as rotational dryland cropping strategies. The objective of this study was to characterize root length density (RLD) and soil water depletion patterns of cowpea [*Vigna unguiculata* (L.) Walp.], grain sorghum [*Sorghum bicolor* (L.) Moench], and sunflower (*Halianthus annuus* (L.)] under no tillage (NT) and stubble mulch tillage (SMT) systems in a Torrertic Paleustoll. Root length density of crops was measured from scanned images of washed root samples obtained from soil cores extracted several times during each of two growing seasons. Soil water contents were measured with a neutron moisture meter to a depth of 2.3 m at weekly intervals throughout each growing season. The RLDs of sorghum and sunflower near the soil surface increased rapidly after planting but thereafter declined whereas subsoil RLD increased throughout the growing season. Residual water contents at harvest were 28 to 93 mm greater ($P < 0.05$) under cowpea as compared to sorghum. As compared to the other crops, most of the additional residual water under cowpea was confined to soil depths between 0.5 and 1.7 m. Soil depths of 1.0 to 1.8 m were the most important source of stored water for sorghum and sunflower towards the end of the season. Deeper rooting and greater soil water extraction below 1.2 m depth were observed for NT as compared to SMT ($P < 0.05$). Results suggest that a rotation of cowpea with sorghum or sunflower would permit the stratified use of soil water and that the storage and crop use of water deep in the profile would be optimized under NT.

I N THE SEMIARID Southern High Plains, plant-available water is the factor most limiting to yield potential. Minimum and NT practices, however, have enabled improvements in water storage efficiency (Jones and Johnson, 1983; Unger, 1984; Baumhardt et al., 1985) thereby potentially allowing for continuous cropping and the elimination of summer fallow. Although continuous sorghum may be feasible (Jones and Popham, 1997), crop rotations may permit greater management of weed infestations (Blackshaw, 2003) and allow for the storage and subsequent utilization of water and nutrients over different soil depths (Merrill et al., 2002). Sorghum and sunflower have rooting systems that can extract stored water to a soil depth of 3.0 m and this contributes to their drought tolerance and adaptation to dryland conditions (Jones and Johnson, 1983; Shackel and Hall, 1984; Jafaar et al., 1993). In contrast, shallow-rooted and short-sea-

son crops such as pulses can leave greater residual soil water, particularly below the root zone (Merrill et al., 2003). Therefore, a rotation consisting of alternating shallow-rooted and short-season crops with deep-rooted crops may improve overall yield and likely reduce yield variability associated with continuous cropping of high water–using crops such as sorghum and sunflower. Stratified use of soil water and nutrients may also improve the overall water use efficiency in cropping systems (Bunting and Kassam, 1988; Gregory, 1989; Roder et al., 1989).

Sorghum, pearl millet [*Pennisetum glaucum* (L.) R. Br.], and maize [*Zea mays* (L.)] are often grown under rotation with cowpea or other legumes (Lightfoot et al., 1987; Kouyaté et al., 1998; Payne et al., 1990). Cowpea, pearl millet, and sunflower can satisfactorily cope with water-deficit periods in semiarid regions using rapid root growth to access available soil water (Steel and Summerfield, 1985, Lightfoot et al., 1987, Bunting and Kassam, 1988, Stone et al., 2001). Cowpea may be especially suitable for use in rotations with sorghum or sunflower because many varieties mature rapidly and thus may have good potential to produce a harvestable crop over a shorter season and use less water. The development of efficient crop rotations that permit stratified use of water requires not only a knowledge of water use by each crop, but also the spatial and temporal aspects of water depletion within the soil profile and throughout the growing season and during winter fallow. Moreover, the success of a particular rotational strategy may be influenced by tillage practices. Our study objectives were to (i) monitor cowpea, sorghum, and sunflower root distribution and associated soil water depletion patterns over two seasons under NT and SMT management and (ii) to evaluate differences in RLD and soil water depletion among crops and between tillage systems.

MATERIALS AND METHODS

The study was conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (35°11′ N, 102°5′ W at an elevation approximately 1170 m above sea level). The soil at the experimental site was Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) with <1% slopes and developed from fine-textured sediments largely of eolian origin. Typically, the Pullman clay loam has a surface plow horizon (Ap) that is about 0.18 m thick with mainly granular structure at the surface (0.05-m depth) and subangular blocky structure below. A dense layer is usually present at approximately 0.2-m depth. Underlying the surface horizon is an argillic (Bt) horizon 0.18 to approximately 1.0 m in depth with texture ranging from silty clay to clay. The 1.5-MPa soil water content exceeds 0.15 m^3 m^{-3} in the Ap and Bt horizons and approaches 0.20 m^3 m^{-3} in the finer-textured layers (Moroke, 2002). Below 1.0-m depth there

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Abbreviations: NT, no tillage; RLD, root length density; SMT, stubble mulch tillage.

Table 1. Agronomic information.

Crop	Year	Planting date	Harvest date	Seeding rate	Root sampling†	Grain yield‡ NT	Grain yield‡ SMT
				1000 plants ha⁻¹	DAP	——— kg ha⁻¹ ———	
Cowpea	2000	12 June	29 Aug.	89	35, 45, 60	776 (87)	812 (77)
	2001	31 May	28 Sept.	89	26, 54, 83	1086 (68)	1121 (42)
Sorghum	2000	6 June	28 Sept.	79	41, 51, 66, 86	2655 (620)	1974 (228)
	2001	31 May	18 Oct.	79	54, 83	3082 (86)	2815 (114)
Sunflower	2000	9 June	19 Sept.	50	38, 48, 63, 83	1045 (110)	968 (102)
	2001	31 May	20 Sept.	50	54, 83	551 (158)	476 (56)

† Days after planting (DAP) that roots were sampled in the field.
‡ Grain yield (±95% confidence interval) for hand-harvested samples (dry weight basis).

is a calcic (Btk) horizon with a clay loam texture and up to 50% calcium carbonates (Unger and Pringle, 1981; Tolk et al., 1995). Additional soil physical properties of the Pullman soil used in this study are presented by Moroke (2002).

The experiment was laid out as a split plot design with NT and SMT as mainplots and crops as subplots with three replicates each. Individual plots were 9-m wide and 30-m long. Cowpea [*V. unguiculata* (L.) Walp, California 8046], grain sorghum [*S. bicolor* (L.) Moench, Dekalb 39Y][1], and sunflower (*Helianthus annuus* L., Dekalb 3970) were planted in 0.76-m rows within each plot and randomized within replicate blocks (Table 1). Previously, NT wheat (*Triticum aestivum* L.) was planted on the experimental area and was harvested in July 1999. The stubble mulch treatment (Jones and Popham, 1997) was implemented after wheat harvest and the area was left fallow until the spring of 2000. Weed control and seedbed preparation in the stubble mulch plots were achieved using a plow with 0.45-m wide sweeps at tillage depth of approximately 0.1 m. Plots were sweep-tilled once after harvest and twice during the spring. Changes in near-surface soil physical properties resulting from sweep tillage are discussed by Schwartz et al. (2003). Weeds on NT plots were controlled using glyphosate [N-(phosphonomethyl) glycine] during fallow. Bicep (atrazine–metolachlor; Ciba-Geigy, Ardsley, NY) was applied as a pre-emergence herbicide to control weeds on sorghum plots and Prowl (pendimethalin; American Cyanamid, Parsippany, NJ) was applied without incorporation before planting on cowpea and sunflower plots. Based on soil tests, a blended fertilizer containing diammonium phosphate was applied to supply 31 kg N ha⁻¹ and 34 kg P ha⁻¹ before planting crops each year. At the end of the growing season, grain was hand sampled in two subplots (four rows by 5 m) to calculate yield.

Soil water contents were measured weekly from 0.10- to 2.30-m depth, at 0.20-m intervals with a neutron moisture

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Table 2. Growing season precipitation and potential evapotranspiration (ET$_0$) for 2000 and 2001 at Bushland, TX.

Period	2000 Precipitation	2000 ET$_0$†	2001 Precipitation	2001 ET$_0$	Average precipitation 1978–1997
			mm		
May	12	250	76	167	68
June	107	184	37	255	77
July	28	259	9	259	69
Aug.	0	290	40	192	75
Sept.	1	235	36	166	63
Oct.	54	100	39	147	32
6 mo	202	1319	237	1185	384
Annual	340	1913	406	1665	504

† All potential evapotranspiration calculations are based on the modified Penman–Monteith equation based on well-watered grass (Allen et al., 1994).

meter (Campbell Pacific Nuclear International, model 503DR, Martinez, CA) from two access tubes per plot, one within and another between rows. The gauge was calibrated in situ at Bushland, Texas using techniques described by Evett and Steiner (1995). Calibration equations were determined separately for the A, Bt, and Btk horizons of the Pullman clay loam soil.

Soil-root samples were collected using a hydraulic drive soil core extractor (57 mm i.d.) at several times throughout the growing season (Table 1). Up to twelve 50-mm length root samples were subdivided from each soil core extracted to a maximum depth of 2.1 m. Soil cores were taken from within and between crop rows at two locations within each plot replicate. Cores were composited by depth and row position. After soaking each sampled core segment overnight in 5% w/w sodium hexametaphosphate solution, a hydropneumatic elutriation system (Smucker et al., 1982) with 0.4-mm screens was used to separate roots from soil. After separation, roots were stored in 50% v/v isopropyl alcohol at 5°C. Extraneous material such as residue and dead roots that were retained on the sieve were manually separated from live roots. Gray scale images were acquired using a flat-bed optical scanner with roots immersed in a tray of water. Total root length for each core sample was calculated with the automatic thresholding algorithm of WinRHIZO (Regent Instruments, Inc., 2001) and counts of skeleton pixels with corrections for displacement direction and root overlap (Bauhus and Messier, 1999).

Mixed linear model analysis for a split-plot design (Littell et al., 1996) was used to test for tillage and crop effects for each year of the experiment. Differences in RLD and water contents between tillage system and among crops were compared for each soil depth increment and day of year using probability level $P = 0.05$. Contrasts were used to test for differences among crops.

RESULTS AND DISCUSSION

Precipitation

Total growing season (May–October) precipitation was 202 and 237 mm in 2000 and 2001, respectively, which is significantly lower than the 20-yr average of 384 mm for the same period (Table 2). Monthly precipitation for both years was significantly lower than the long-term average except for October of both years. In 2000, there was no significant precipitation during the cropping season as only 29 mm (14% of average) fell between June and October. In both growing seasons, potential evapotranspiration exceeded precipitation by fivefold (Table 2). Due to high evaporative demands during these two years, water received during small pre-
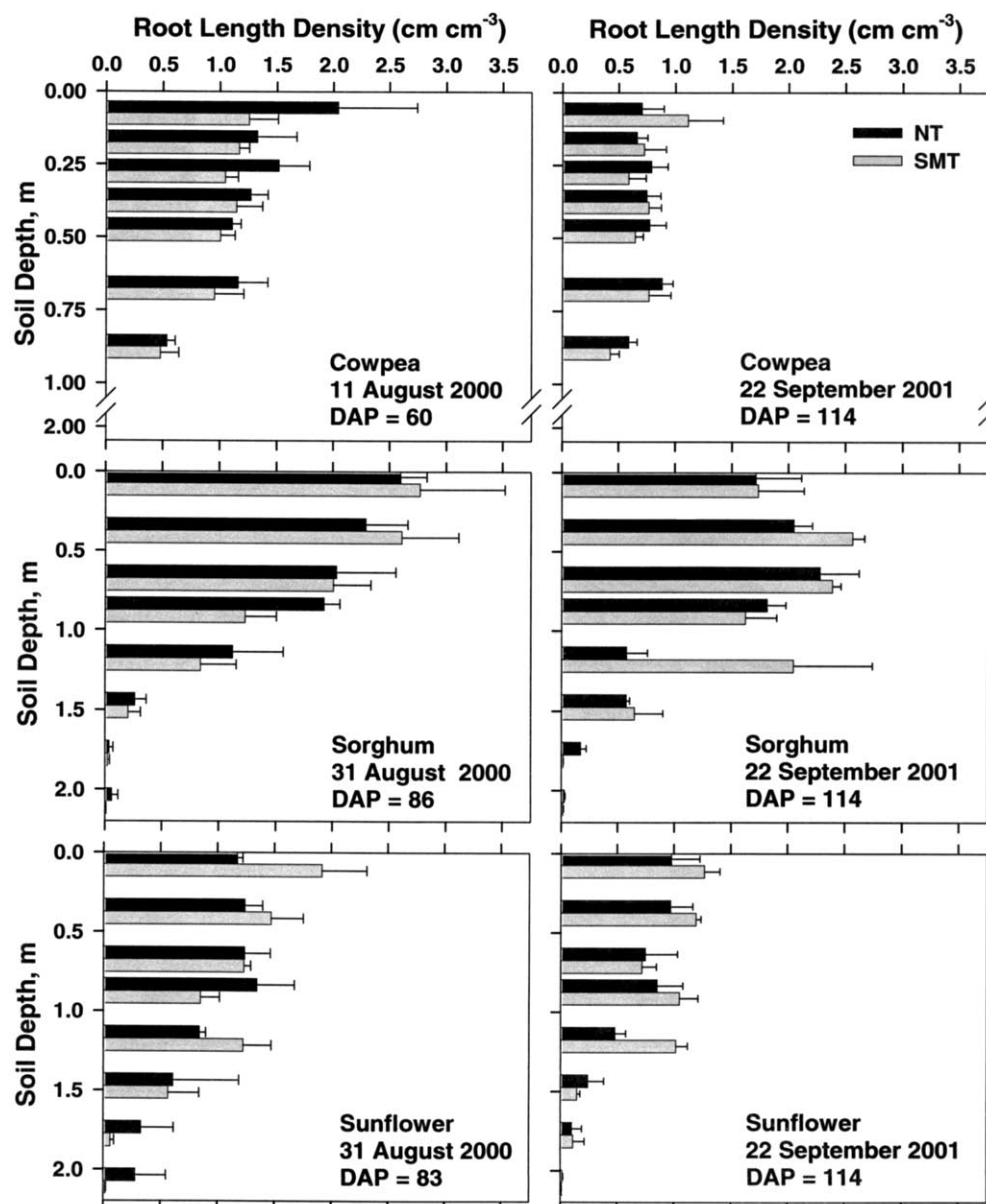
Fig. 1. Root length density (RLD) of crops for selected depths near the end of the 2000 and 2001 growing seasons. Error bars are ±1 SE. Note enlarged *y*-axis scale for cowpea. Days after planting (DAP).

cipitation events were likely lost to evaporation (Ji and Unger, 2001). Precipitation was better distributed throughout the 2001 growing season but still much lower than the long-term average. Drainage was estimated throughout each growing season by calculating weekly flux based on the gradient in water content measured at 2.1 and 2.3 m, water retention measurements of this layer (Moroke, 2002), and conductivity estimates for similar calcic horizons (Baumhardt and Lascano, 1993). Estimated seasonal fluxes under all crops were negligible ($P > 0.05$) except for sunflower in 2000 where it was estimated that 50-mm water moved upward into the 2.2-m control section probably as a result of intense soil drying below 1.7 m by root uptake of water.

Root Growth and Distribution

Patterns of root growth in the soil profile for all crops were characterized by the greatest RLD occurring in the upper 0.5 m of the soil profile and decreasing progressively with depth (Fig. 1). During the 2000 season, RLD of sorghum and sunflower near the surface increased rapidly at the beginning of the season and decreased after about midseason (Fig. 2). Root length density in the subsoil, however, tended to increase throughout the growing season, particularly for sorghum and sunflower. In most cases, tillage did not significantly ($P > 0.05$) affect the RLD of crops at all sampling depths throughout both growing seasons. However, in the later part of the 2000 season, there was a tendency for RLDs deeper in the profile to be greater in NT as compared to SMT plots (Fig. 1). Total root length over the entire profile was not influenced by tillage and attained maximum values of 300, 220, and 110 cm cm^{-2} for sorghum, sunflower, and cowpea, respectively.

Root length density can vary greatly among crop species under differing environmental conditions (e.g., Fisher
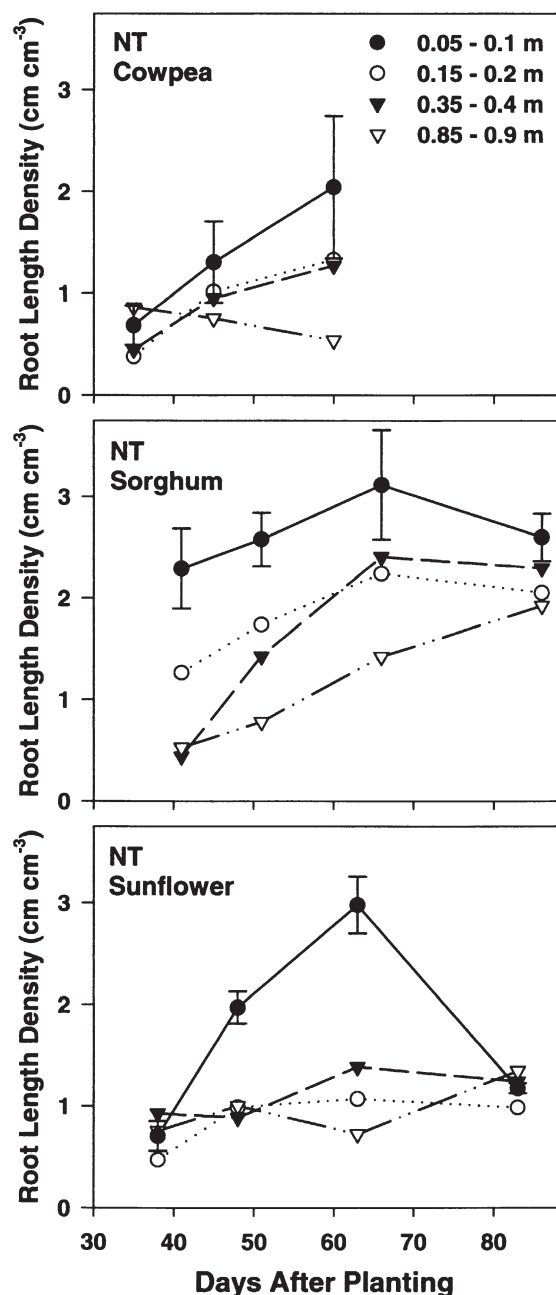
Fig. 2. Root length density (RLD) of cowpea, sorghum, and sunflower during the 2000 growing season under no tillage (NT) at selected soil depth increments. Error bars (±1 SE) are shown for the 0.05- to 0.1-m depth increment.

Salih et al. (1999) measured a maximum RLD of 1.9 and 3.5 cm cm^{-3} for two sorghum cultivars under dry conditions (washed soil cores, 2-mm sieve, intersection method). However, RLD increased to a maximum of 5.1 cm cm^{-3} for one of the cultivars under conditions where soil water was not limiting. The maximum measured RLD of sunflower under this study was 2.97 and 2.17, and 1.20 and 1.27 cm cm^{-3} under NT and SMT in 2000 and 2001, respectively. Because of surface sealing from intense rains in early June, sunflower stand establishment was poor in 2001. Poor establishment of sunflower in 2001 probably led to the lower RLD and rooting depth for this season (Fig. 1).

Commonly, RLD under humid or subhumid climates is greater near the soil surface and decreases with increasing soil depth, but this growth pattern can be reversed under water limiting conditions (Merrill and Rawlins, 1979; Fisher and Dunham, 1984; Miyazaki et al., 1993; Merrill et al., 2002). In 2000, RLD of sorghum and sunflower near the surface under NT (Fig. 2) and under SMT (not shown) tended to decrease later in the season possibly because of root senescence and eventual death brought on by intense evaporative drying and high soil temperatures. In contrast, RLD at lower depths tended to increase throughout the growing season. A similar decrease in the RLD of cowpea later in the season may not be evident under NT (Fig. 2) because the crop was harvested before the final root sampling date in 2000. In 2001, changes in RLD near the soil surface between the last two sampling dates were less pronounced than in 2000 probably because of the additional rainfall received in August 2001. Nevertheless, these results suggest that the root systems of sorghum and sunflower may have the ability for compensatory growth to increase or relocate maximal RLD to regions of greater water content in the soil profile thereby maintaining plant growth under dry conditions (Rendig and Taylor, 1989).

Soil Water Depletion Rates and Patterns

Soil water content distributions with respect to soil depth for cowpea, sorghum and sunflower throughout the 2000 and 2001 growing seasons and for each of the tillage treatments are shown in Fig. 3 and 4. In 2000, cowpea water depletion was concentrated in the upper 1.50 and 1.30 m under NT and SMT, respectively. In 2001, however, decreases in the soil water content profile below 1.5 m suggest that cowpea extracted water to depths exceeding 2.0 m, especially under NT. Supplemental precipitation in August and September extended the 2001 growing season for this indeterminate cowpea cultivar (Table 1) and likely permitted greater depletion of soil water at greater depths as compared to the 2000 season. Significant amounts of soil water were depleted below 1.5 m under sorghum and sunflower. Sunflower depleted water contents below 1.5 m to a greater extent in 2000 as compared to the 2001 growing season. Sunflower establishment was poor in 2001, and this resulted in shallower rooting depth compared with the 2000 season (Fig. 1).

Initial water contents at the beginning of the 2000

and Dunham, 1984; Bunting and Kassam, 1988). The range in RLDs measured for the three crops exhibited a considerable degree of variation but reflect RLD measurements found in the literature for dryland (water limiting) conditions. Maximum RLDs for cowpea were 2.04 and 1.26 cm cm^{-3}, and 1.52 and 0.63 cm cm^{-3} under NT and SMT in 2000 and 2001, respectively. Timsina et al. (1993) reported a similar maximum RLD of 2.3 cm cm^{-3} from scanned images of cowpea roots obtained from washed soil cores. For sorghum, the maximum RLDs were 3.20 and 2.47 cm cm^{-3}, and 2.54 and 2.79 cm cm^{-3} under NT and SMT in 2000 and 2001, respectively.
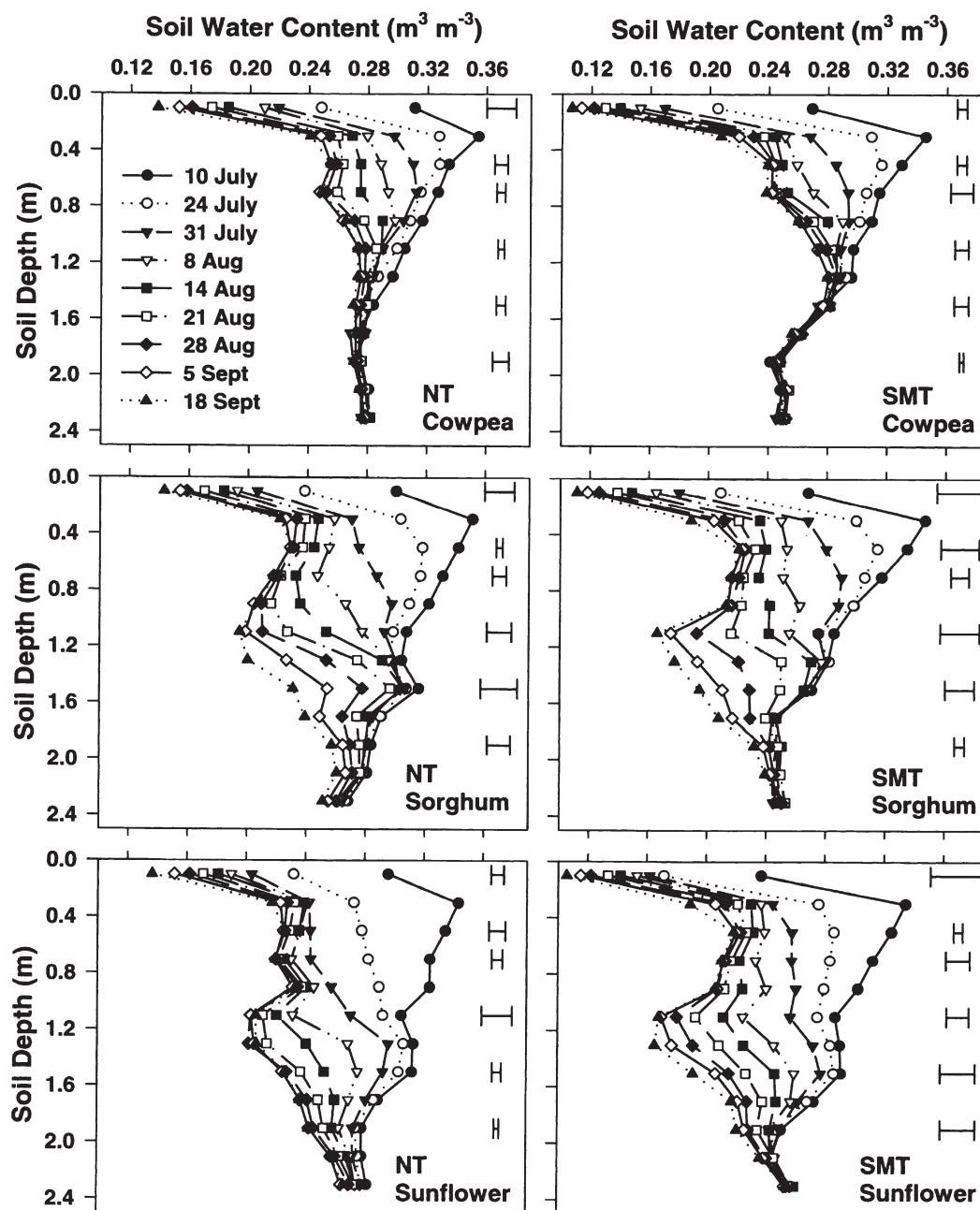
Fig. 3. Soil water contents under cowpea, sorghum, and sunflower as a function of soil depth under no tillage (NT) and stubble mulch tillage (SMT) in 2000. Error bars for selected depths are ± 1 SE of the mean change in water content between the first and last measurement times.

season were similar among crops at all depths, however, NT plots had significantly ($P = 0.0013$) greater water contents than the SMT plots at the surface (0–0.2 m) depth increment (Fig. 3) because of reduced evaporation during fallow. Initial water contents at the beginning of the 2001 season were also greater under NT plots near the surface as compared to SMT (Fig. 4) but the water content distributions were also influenced by the previous crop.

In 2000, total soil water depletion to a 2.4-m depth averaged 114 mm across tillage treatments for cowpea but was nearly twice as much for plots planted to sorghum and sunflower (Table 3). Statistical comparisons of soil water contents at the end of the first growing season (Fig. 3) indicates the additional water extracted by sorghum and sunflower as compared to cowpea were principally derived from the 0.9- to 1.7-m soil depths under NT and 0.5- to 1.1-m soil depths under SMT. Recharge of soil water throughout the winter fallow was similar under NT and SMT but significantly greater under sorghum as compared to cowpea. These differences were not a result of drainage because precipitation penetrated to a maximum depth of 1.5 m and water contents at lower depths did not change significantly during this time period. Lower fallow efficiencies under cowpea and sunflower as compared to sorghum (Table 3) may have resulted from increased runoff and evaporation as a consequence of lower aboveground biomass
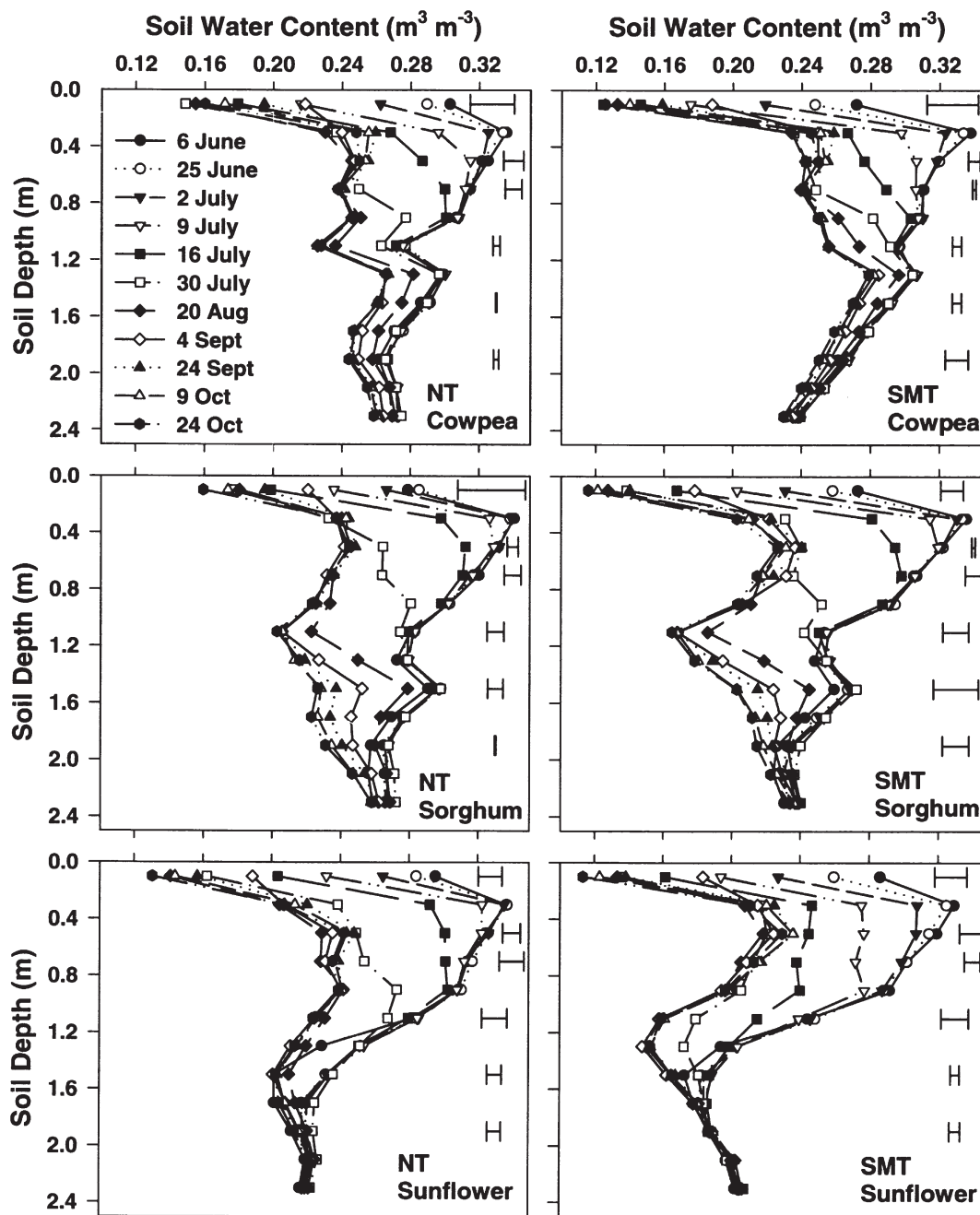
Fig. 4. Soil water contents under cowpea, sorghum, and sunflower as a function of soil depth under no tillage (NT) and stubble mulch tillage (SMT) in 2001. Error bars for selected depths are ±1 SE of the mean change in water content between the first and last measurement times.

production and the correspondingly low residue cover under both cowpea and sunflower. During the 2001 season, soil water depletion was significantly greater under sorghum as compared to cowpea and sunflower (Table 3). Overall, residual water contents at the end of the growing season under cowpea ranged from 28 to 93 mm greater than under sorghum for these two years. Similar comparisons of water depletion by Merrill et al. (2003) in North Dakota also demonstrated that from 80 to 110 mm more soil water following dry peas as compared to sunflower. In the present study, soil water gains obtained using a pulse crop seemed to be partially offset

by lower winter fallow efficiencies under the warmer climate of the Southern Great Plains.

Tillage did not significantly influence the rate of total soil water depletion during the 2000 and 2001 growing seasons (Table 3). However, greater RLDs (Fig. 1) and correspondingly greater decreases in water content deeper in the profile for all crops under NT suggest that water was extracted from deeper depths under NT as compared to SMT. Consequently, greater grain yields under NT (Table 1) may have resulted from improved access to stored soil water deeper in the profile as well as reduced evaporation near the surface. Paired compari-

Table 3. Soil water contents to a 2.4-m depth in 2000 and 2001 and corresponding soil water depletions and fallow efficiencies.

Crop	Tillage	Total soil water				Soil water depletion†		Fallow efficiency‡
		10 July 2000	18 Sept. 2000	6 June 2001	24 Oct. 2001	2000	2001	2000–2001
		mm (2.4 m)$^{-1}$						
Cowpea	NT	726	609	702	578	117	124	0.25
Sorghum	NT	738	528	690	538	210	152	0.44
Sunflower	NT	735	534	627	508	201	119	0.25
Cowpea	SMT	685	575	689	575	111	114	0.31
Sorghum	SMT	674	482	641	476	192	165	0.43
Sunflower	SMT	676	476	580	440	199	140	0.28
LSD (0.05)		39.7	36.4	42.3	34.7	20.5	22.7	0.11

† mm of water depleted from 10 July to 18 Sept. in 2000 and 6 June to 24 Oct. in 2001.
‡ Change in storage divided by precipitation (368 mm) between 18 Sept. 2000 and 6 June 2001.

sons of soil water depletion below 1.2-m depth for cowpea and 1.6-m depth for sorghum indicate that approximately 8 mm (P = 0.0231) and 14 mm (P = 0.0013) more soil water was depleted under NT as compared to SMT for cowpea and sorghum, respectively. No tillage sunflower depleted 5 mm more water than SMT sunflower below 1.6-m soil depth although these differences were not significant. Deeper extraction of soil water under NT may be a result of more rapid establishment and growth of crops under more favorable conditions, especially greater soil water contents near the surface (Fig. 3 and 4). This synergistic effect of improved water status permitting water extraction to greater depths has also been reported by Merrill et al. (1996).

All soil water content distributions for sorghum and sunflower (Fig. 3 and 4) toward the end of the growing season exhibited a region below 1.0-m depth where water contents were depleted to a greater extent than the region above. In addition, the relatively large water depletion rates at the 1.0- to 1.4-m and 1.4- to 1.8-m depth increments (Fig. 5) suggest that this region was important source of stored water for sorghum and sunflower later in the growing season. The soil depth of approximately 1.0 m in the soils of this field roughly corresponds to the interface between a calcic horizon below and a fine-textured Bt horizon above. Apparently, the calcic horizon was an important source of stored water for sorghum and sunflower in the latter part of the growing season. Water depletion in the calcic horizon under cowpea was significantly lower as compared to sunflower and sorghum probably because RLDs of cowpea at depths greater than 1.0 m were insignificant (Moroke, 2002). In addition, cowpea may exert a lower suction and hence smaller water uptake as compared to sorghum and sunflower (Bunting and Kassam, 1988).

The rate of soil water depletion by all crops exhibited a trend of maximum water extraction from successively deeper layers as the season progressed (Fig. 5). Significant water depletion by cowpea was limited to the upper 1.0-m soil layer while sorghum and sunflower effectively extracted water up to 1.8-cm depths. At about 50 d after planting, soil water content was significantly ($P < 0.05$) lower under sunflower than both cowpea and sorghum, principally at soil depths of 0.3 to 0.9 m. These differences are demonstrated by a greater soil water depletion rate at the 0.6- to 1.0-m depth increment early in the 2000 growing season for sunflower as compared to sor-

ghum and cowpea (Fig. 5). However at 80 to 90 d after planting, soil water depletion rates at all soil depths under sunflower in both NT and SMT plots approached zero. In contrast, water depletion rates under sorghum during this period were near maximal at the 1.0- to 1.8-m soil depth increments (Fig. 5). Toward the end the season, differences in soil water content throughout the entire profile between sorghum and sunflower were not significant. High rates of soil water depletion by sunflower in deep soil layers resulting from rapid rates of vertical root extension have also been reported by Stone et al. (2001).

CONCLUSIONS

Crop species and year significantly influenced soil water depletion patterns under extreme water limiting conditions. Cowpea had shallower rooting depths than sunflower and sorghum. Most of the water depleted under cowpea was at soil depths less than 1.0 m. Greater amounts of precipitation in the later part of one growing season may have permitted greater root extension and water depletion at depths greater than 1.0 m for this indeterminant cowpea cultivar. Water contents in a 2.4-m profile after cowpea ranged from 28 to 93 mm more than after sorghum but these gains were partially offset by lower winter fallow efficiencies under cowpea. Utilization of a determinant cowpea cultivar combined with NT management would help maximize the amount of water available for subsequent crops.

The RLD of crops during an extremely dry season tended to decrease mid-season at shallow soil depths whereas RLD increased throughout the growing season at deeper soil depths. These changes parallel the trend in maximum water depletion from successively deeper layers as the season progressed. The rate of root growth and water depletion was significantly greater under sunflower as compared to sorghum during the 2000 growing season. Because sorghum reached maturity later in the growing season, however, total water depletion in 2000 was approximately the same for sunflower and sorghum. During 2001, poor establishment of sunflower limited root growth and water extraction from depths greater than 1.5 m and was probably responsible for the lower water depletions as compared to sorghum in 2001. Below 1.0-m soil depth, the calcic horizon was an important source of stored water for sorghum and sunflower in the latter part of the growing season.
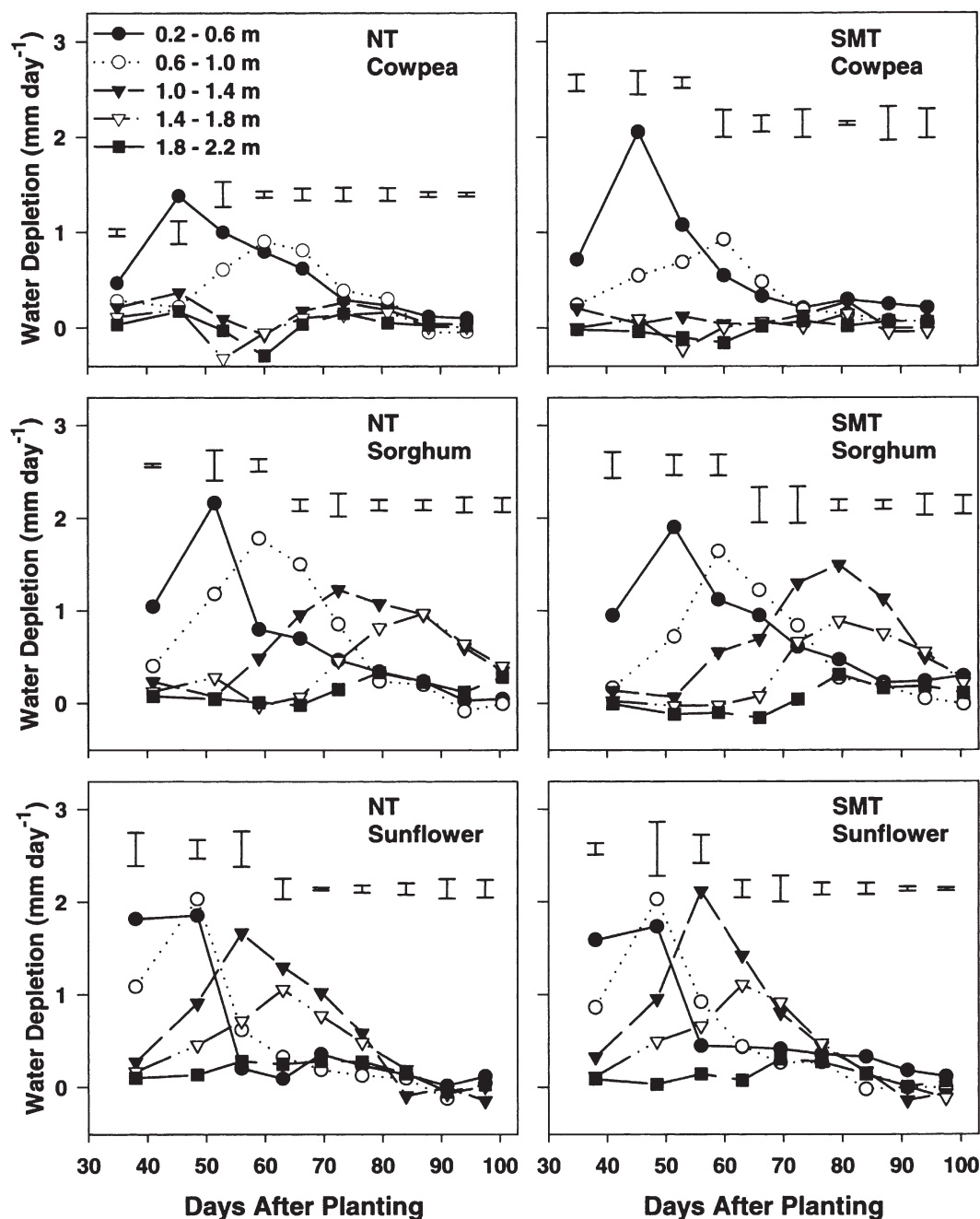
Fig. 5. Daily water depletion rate [mm H_2O (0.4 m soil depth)$^{-1}$ d^{-1}] for cowpea, sorghum, and sunflower at selected soil depths throughout the 2000 growing season. Error bars are ±1 SE of the mean water depletion rate for the depth increment 0.6 to 1.0 m.

Root length densities and seasonal water depletion in 2000 were slightly greater at deeper depths under NT as compared to SMT for all crops. This may have resulted from improved water status near the surface of NT plots that allowed a more rapid crop establishment and growth early in the season and higher grain yields. Results from this study suggest that differences in rooting and soil water extraction patterns among crops could permit more efficient use of soil water by substituting a pulse crop such as cowpea into the summer fallow phase of a rotation. Use of NT management in conjunction with such a rotation would not only permit greater storage of water throughout the entire soil profile but also may allow access to stored water by subsequent crops with deeper rooting systems.

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